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ACTIVE AND PASSIVE REMOTE SENSING OF ICE

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ACTIVE AND PASSIVE REMOTE SENSING OF ICE

Principal Investigator: Jin Au Kong

FINAL REPORT

Under the sponsorship of the ONR contract N00014–83–K–0258, we have published 3 books, 66 journal and conference papers and 10 student theses.

Fully polarimetric scattering properties of earth terrain media are studied with three-layer random medium model. The top scattering layer is modeled as an isotropic random medium which is characterized by a scalar permittivity. The middle scattering layer is modeled as an anisotropic random medium with a symmetric permittivity tensor whose optic axis can be tilted depending on the preferred alignment of the embedded scatterers. The bottom layer is considered as a homogeneous half-space. Volume scattering effects of both random media are described by three-dimensional correlation functions with variances and correlation lengths corresponding to the strengths of the permittivity fluctuations and the physical sizes of the inhomogeneities, respectively. The strong fluctuation theory is used to derive the mean fields in the random media under the bilocal approximation with sinularities of the dyadic Green's functions properly taken into consideration. With the discrete scatterer concept, effective permittivities of the random media are calculated by two-phase mixing formulas. Then, the distorted Born approximation is used to calculate the covariance matrix which describes the fully polarimetric scattering properties of the remotely sensed media. The polarimetric information is useful in the identification, classification, and radar image simulation of earth terrain media.

To observe polarimetric scattering directly from earth terrain media such as vegetation, meadow, and ice, the three-layer configuration is first reduced to two-layer by removing the top layer. Such media exhibit reciprocity as experimentally manifest in the close proximity of the measured backscattering radar cross sections σ_{VH} and σ_{HV} and theoretically established in the random medium model with a symmetric permittivity tensor. In this case, the covariance matrix is a 3 by 3 matrix with the lower triangle containing elements which are complex conjugates of the corresponding elements in the upper triangle. The results obtained with the two-layer configuration show that polarimetric information carried by the complex correlation coefficient (ρ) is helpful in identifying isotropic versus anisotropic media due to the distinctive characteristics that each of the two media imposes on ρ. For an isotropic medium, the value of ρ is close to 1 over the range of incident angles under the single scattering approximation. Whereas for an anisotropic medium, the magnitude of ρ attains a maximum value at a particular incident angle θ_ρ and decays as the incident angle departs from θ_ρ. Furthermore, the correlation coefficient conveys information about the optic-axis tilted angle of the anisotropic random medium. When the optic axis is not tilted, θ_ρ is at normal incident. As the optic axis becomes tilted, θ_ρ deviates away from normal incident. It should also be noted that the tilt of the optic axis is directly related to the non-zero depolarization terms in the covariance matrix which becomes very small for an untilted anisotropic or isotropic medium. Thus, the fully polarimetric information is important in the remote sensing of earth terrain.

The three-layer random medium has the capability of accounting for polarimetric scattering from earth terrain media under the effects of weather, seasonal variation, and atmospheric conditions such as forest under mist, meadow under fog, and ice under snow. The effects on polarimetric wave scattering due to the top layer are identified by comparing the three-layer model results with those obtained from the two-layer model. Consider first the case of a low-loss scattering layer covering the tilted anisotropic scattering layer. The enhancement of the radar returns due to dry-snow cover on top of first-year sea ice observed in the experimental data can be explained using the three-layer configuration. Also, the low-loss top layer can give rise to the oscillation on the radar returns as a function of incident angle due to the boundary effect. The oscillation can also be seen on the real and imaginary parts of the correlation coefficient (ρ). Interestingly, the magnitude of ρ does not show the oscillation while clearly retaining the similar characteristics as observed directly

from the two-layer configuration. Thus, the correlation coefficient can carry information from both the covering low-loss isotropic layer and the lower tilted anisotropic layer in a rather distinctive manner. As the thickness of the top layer increases, the value of ρ at a given incident angle increases meaning that the top layer can weaken the anisotropic effect of the lower layer. This masking effect is clearly seen when the top layer becomes lossy. In this case, the radar returns are diminished instead of being enhanced. In this application of the random medium model to polarimetric remote sensing of earth terrain, the encountered media are reciprocal and can be characterized by symmetric permittivity tensors.

A radar clutter model is used to simulate fully polarimetric returns for a stepped frequency radar. The purpose is to create synthetic site dependent clutter signatures that can be utilized in a hardware-in-the-loop test system. The fully polarimetric, multi-frequency, multi-incident angle random medium model is employed to generate normalized backscatter coefficients of terrain clutter. This model is used to generate the polarimetric terrain clutter covariance matrices for each of N high resolution range bins, at each of the M discrete frequencies. The random medium model allows us to include the effect of the terrain local incident angle on the clutter covariance matrix elements. In the simulation, we assume that there is a single clutter class within each of the N range bins, although the depression angle may vary from bin to bin. The covariance matrices are decomposed and multiplied by complex Gaussian noise in order to generate the normalized electric fields in the backscattering direction for each of the N range bins, at each of the M discrete frequencies. These fields are then coherently added, taking into account the effects of both terrain elevation and range. This yields a single frequency polarimetric return that a radar would measure from the specified terrain. The radar return for each of the other discrete frequencies is calculated in a similar manner. The result is the clutter's low resolution range polarimetric profile, i.e., the backscattered signal response within the beam footprint of the radar antenna. Each discrete frequency is simulated and the effects of shadowing and overlay are taken into account. The simulation produces coherent phase-history clutter returns which can be coherently superimposed on the target phase-history returns. The combined (or clutter only) returns are processed to obtain either (1) the coherent, high resolution range profile or (2) the noncoherent, autocorrelation range profile.

Supervised and unsupervised classification procedures are developed and applied to synthetic aperture radar (SAR) polarimetric images in order to identify its various earth terrain components. For the supervised classification processing, the Bayes technique is utilized to classify fully polarimetric and normalized polarimetric SAR data. Simpler polarimetric discriminates, such as the unnormalized and normalized magnitude response of the individual receiver channel returns, in addition to the phase difference between the receiver channels are also considered. Covariance matrices are computed for each terrain class from selected portions within the image where ground truth is available, under the assumption that the polarimetric data has a multivariate Gaussian distribution. These matrices are used to train the optimal classifier, which in turn is used to classify the entire image. In this case, classification is based on determining the *distances* between the training classes and the observed feature vector, then assigning the feature vector to belong to that training class for which the distance was minimum. Another processing algorithm based on comparing general properties of the Stokes parameters of the scattered wave to that of simple scattering models is also discussed. This algorithm, which is an unsupervised technique, classifies terrain elements based on the relationship between the orientation angle and handedness, or ellipticity, of the transmitted and received polarization state. These classification procedures will be applied to San Francisco Bay and Traverse City SAR imagery, supplied by the Jet Propulsion Laboratory. It is shown that fully polarimetric classification yields the best overall performance. Also, in some selected areas where the observed amplitudes of the returns are quite different than that of the training data, classification techniques not based on the absolute amplitudes of the returns, e.g., the normalized polarimetric classifier, produced a more consistent result with respect to the ground truth data.

The normalized polarimetric classifier is proposed such that only the relative magnitudes and phases of the polarimetric data will be utilized to discriminate terrain elements. For polarimetric data with arbitrary probability density function (PDF), the distance measures of the normalized polarimetric classifier based on a general class of normalization functions are shown to be equivalent to one another. The normalized polarimetric classifier thus derived will be optimal among all normalization schemes, when the system absolute calibration factors are common to all polarimetric channels. Further assuming a

multivariate complex Gaussian distribution for the un-normalized data, the distance measure of the normalized polarimetric classifier is given explicitly and turns out to be also independent of the number of scatterers. The usefulness of the normalized polarimetric classifier is demonstrated by the classification of trees and grass in the experimental data obtained from Lincoln Laboratory. The classification error is shown to be the smallest among those of magnitude ratio or phase difference classifications.

A three-layer random medium model is developed to study the fully polarimetric scattering properties of earth terrain. The top layer is modeled as an isotropic random medium, the middle layer as an anisotropic random medium, and the bottom layer as a homogeneous half-space. Volume scattering effects of both random media are characterized by correlation functions in which variances and correlation lengths describe strengths of permittivity fluctuations and physical sizes of embedded inhomogeneities, respectively. The anisotropic effect of the middle layer is attributed to specific structure and alignment of the scatterers. With the strong fluctuation theory, the mean fields in the random media are derived under the bilocal approximation with singularities of the dyadic Green's functions properly taken into consideration. With the discrete scatterer concept, effective permittivities of the random media are calculated by two-phase mixing formulas. Then, the distorted Born approximation is used to calculate the covariance matrix which describes the fully polarimetric scattering properties of the terrain and is used in radar image simulation and earth terrain identification and classification.

A two-layer random medium model has been successfully applied to polarimetric remote sensing of earth terrain such as vegetation, meadow, and ice layer. The results obtained with the three-layer configuration have the capability of accounting for polarimetric scattering from earth terrain under the effects of weather, seasonal variation, and atmospheric conditions such as forest under mist, meadow under fog, and ice under snow. The effects on polarimetric wave scattering due to the top layer are identified by comparing the three-layer model results with those obtained from the two-layer model. The enhancement of the radar returns due to dry-snow cover on top of first-year sea ice observed in the experimental data can be explained using the three-layer random medium model. The theoretical results are illustrated by comparing the calculated covariance matrices with the polarimetric measurement data.

There is a considerable interest in determining the optimal polarizations that achieve maximum contrast between two scattering classes in radar polarimetric images for the purpose of terrain discrimination. In this paper, we present a systematic approach for obtaining the optimal polarimetric matched filter which produces maximum contrast between two scattering classes, each represented by its respective covariance matrix.

To accomplish this, we derive a linear weighting vector that maximizes the expected power return ratio, i.e., the contrast ratio between the two scattering classes. The maximization procedure involves solving an eigenvalue problem where the eigenvector yielding this maxima will correspond to the optimal polarimetric matched filter. Then, through use of polarization synthesis, it is demonstrated that when this weighting vector is utilized to process fully polarimetric radar images, the maximum contrast between the two respective classes results. The sub-optimal problem of a fixed transmitting polarization is also considered. In this case, the received polarization is optimized such that a maxima in the contrast ratio is obtained under this constraint. To exhibit the physical significance of this filter, we transform it into its associated transmitting and receiving polarizations, in terms of their horizontal and vertical vector components.

This technique is then applied to radar polarimetry obtained from the Jet Propulsion Laboratory. It is shown, both numerically and through the use of radar imagery, that maximum image contrast can be realized when data is processed with the optimal polarimetric matched filter.

For active and passive microwave remote sensing of sea ice, the two-layer uniaxial random medium model is applied to study the volume scattering and anisotropic effects which are attributed to embedded brine inclusions. In the model, the correlation function is the direct link between the electrical behavior and physical properties of embedded brine inclusions. The spatial distribution, size, elongated structure, and preferred alignment of embedded brine inclusions can be described by variances, correlation lengths, and the form of the correlation function. We have extracted a correlation function of exponential form from the photograph of a horizontal thin section prepared from a sample of artificially grown saline ice that closely resembled Arctic congelation sea ice. It is found that the extracted correlation lengths are consistent with the published average size of brine pockets. With the application of strong fluctuation theory and the bilocal approximation, the

effective permittivity tensor is derived in the low frequency limit for an unbounded uniaxial random medium with two-phase mixtures. Using the extracted correlation length, the effective permittivity tensor is computed as a function of fractional volume of brine inclusions and compared with the in situ dielectric measurements at microwave frequencies of 4.8 and 9.5 GHz. (Electromagnetic theory, sea ice, two-layer uniaxial random medium model, volume scattering, anisotropic, brine inclusions, Arctic congelation sea ice, strong fluctuation theory, bilocal approximation, effective permittivity tensor, two-phase mixture, fractional volume.) 0659 Random media and rough surfaces, 0669 Scattering and diffraction, 0689 Wave propagation

A three-layer random medium model is developed to investigate effects of snow cover on the sea ice signature for microwave remote sensing. The volume scattering and anisotropic effects due to embedded inhomogeneities in the snow-covered sec ice are studied with the wave theory. The snow layer is modelled as an isotropic random medium and the sea ice as an anisotropic random medium. Volume scattering effects are caused by granular ice particles and water contents in snow and by brine inclusions and air bubbles in sea ice, respectively. The anisotropic effect is attributed to the elongated structure of brine inclusions with a preferred alignment between ice platelets. In the random medium model, the essential quantity is the correlation function which contains important physical parameters such as variances and correlation lengths for characterizing the strength of the permittivity fluctuation, the physical size, and the geometrical structure of scatterers. We have extracted correlation function from digitized image of saline ice sample grown in the outdoor tank at CRREL. The calculated correlation lengths are consistent with reported average size of brine pockets.

The strong fluctuation theory is applied to account for the distinct permittivity difference between air, ice particles, water, and brine inclusions. First of all, singularities of the dyadic Green's functions for snow and sea ice are properly considered. Then, the mean fields in both media are derived by the bilocal approximation. With the discrete scatterer concept, effective permittivities for dry snow and first-year sea ice are computed by two-phase mixing formulas. The effective permittivities of sea ice calculated as a function of fractional volume of brine inclusions are found to be consistent with the published results obtained from slab ice samples. For calculating effective permittivities of wet snow and multi-year sea ice, three-phase mixing formulas are used since wet snow consists of air,

ice grains, and water and multi-year sea ice is composed of pure ice, brine inclusions, and air bubbles. Finally, the bistatic scattering and backscattering coefficients are computed with the distorted Born approximation. The results are illustrated by comparing the backscattering coefficients as a function of incident angle with experimental data from controlled field measurements.

A generalized K-distribution is proposed to model the statistics of the fully polarimetric returns from the terrain cover. In the past, K-distribution has been used successfully to characterize the intensity distribution of single polarization returns. Recently, fully polarimetric synthetic aperture radar (SAR) data with polarizations HH, HV, and VV have been proven useful in remote sensing of earth terrain and in this paper we generalize the K-distribution to model fully polarimetric terrain radar clutter. The generalized K-distribution is a better description of the statistics of the SAR polarimetric data than the Gaussian distribution and would be useful in identification and classification of terrain types in the SAR polarimetric data.

In general, all polarization returns of each single polarimetric measurement are correlated with different variances. Therefore, we assume an n-dimensional anisotropic random walk model where the coordinate components of each step are characterized by a covariance matrix and the number of steps or scatterers is of negative binomial distribution with parameter α. The anisotropy in the model refers to the fact that the the covariance matrix is not proportional to an identity matrix. A generalized K-distribution for polarimetric data is derived when the average number of steps approaches to infinity. The K-distribution is also generalized to the non-zero mean case, which can be used to model the statistics of transmitted electromagnetic wave through atmosphere. It is found that if a zero-mean K-distributed random vector is normalized by its Euclidean norm, the joint probability distribution of the normalized quantities is independent of the parameter α and is the same as that derived from a zero-mean Gaussian-distributed random vector. The results are illustrated by analyzing the normalized intensity moments of the polarimetric SAR images provided by the Jet Propulsion Laboratory and comparing them with the generalized K-distributed polarimetric model.

The volume scattering effects of snow-covered sea ice are studied with a three-layer random medium model for microwave remote sensing. The strong fluctuation theory and the bilocal approximation are applied to calculate the effective permittivities for snow and sea ice. The wave scattering theory in conjunction with the distorted Born approximation is then used to compute bistatic coefficients and backscattering cross sections. Theoretical results are illustrated by matching experimental data for dry snow-covered thick first-year sea ice at Point Barrow. The radar backscattering cross sections are seen to increase with snow cover for snow-covered sea ice, due to the increased scattering effects in the snow layer. The results derived can also be applied to the passive remote sensing by calculating the emissivity from the bistatic scattering coefficients.

The remote sensing of sea ice is studied with the two-layer random medium model where a correlation function is used to characterize the randomly fluctuating part of the permittivity. Due to the shape and distribution of the brine inclusions, the sea ice is generally anisotropic. We assume the sea ice to be uniaxial and extract correlation functions from a photograph of an artificially grown ice sheet sample. The sizes and distributions of the brine pockets are related to the correlation lengths and the shapes of the correlation functions. The effective permittivity of sea ice is calculated with the strong fluctuation theory assuming a two-phase mixture consisting of pure ice and brine inclusions. The calculated effective permittivities are found to be consistent with the published results obtained from slab ice samples.

A systematic approach for the identification of terrain media is developed using the optimum polarimetric classifier. The covariance matrices for various terrain cover are computed from theoretical models of random medium by evaluating the full polarimetric scattering matrix elements. The optimal classification scheme makes use of a quadratic distance measure and is currently applied to classify a vegetation canopy consisting of both trees and grass. Experimentally measured data are used to validate the classification scheme. Theoretical probability of classification error using the full polarimetric matrix is compared with classification based on single features which include the phase difference between the VV and HH polarization returns. It is shown that the full polarimetric results are optimal and provide better classification performance than single feature measurements. The application of this classification scheme to sea ice will be explored.

The Mueller matrix and polarization covariance matrix are described for polarimetric radar systems. The clutter is modelled by a layer of random permittivity, described by a three-dimensional correlation function, with variance, and horizontal and vertical correlation lengths. This model is applied, using the wave theory with Born approximations carried to the second order, to find the backscattering elements of the polarimetric matrices. It is found that 8 out of 16 elements of the Mueller matrix are identically zero, corresponding to a covariance matrix with four zero elements. Theoretical predictions are matched with experimental data for vegetation fields.

Geophysical media encountered in nature are generally mixtures of dielectrically different materials. When a dielectric mixture is considered macroscopically, i.e., the scale of interest is much larger than the correlation length of the inhomogeneities of the material, it can be assigned an effective permittivity that relates the average macroscopic displacement and the electric field. This effective permittivity can be calculated through a quasistatic analysis which restricts the results of this dielectric mixture theory to cases where the size of the inhomogeneities is much smaller than the wavelength. The limitation resulting from this is that the effective permittivity, which can have complex values, only includes the absorption losses but not the scattering losses.

We have studied the volume scattering effects of snow-covered sea ice with a three-layer random medium model for microwave remote sensing. The strong fluctuation theory and the bilocal approximation are applied to calculate the effective permittivities for snow and sea ice. The wave scattering theory in conjunction with the distorted Born approximation is then used to compute bistatic coefficients and backscattering cross sections. Theoretical results are illustrated by matching experimental data for dry snow-covered thick first-year sea ice at Point Barrow. The radar backscattering cross sections are seen to increase with snow cover for snow-covered sea ice, due to the increased scattering effects in the snow layer. The results derived can also be applied to the passive remote sensing by calculating the emissivity from the bistatic scattering coefficients.

The scattering of electromagnetic waves from a randomly perturbed peridic surface is solved using the Extended Boundary Condition (EBC) method. The scattering from periodic surface is solved exactly using the EBC method and this solution is used in the small perturbation method to solve for the scattered field from a randomly perturbed periodic surface. The random perturbation is modeled as a Gaussian random process and the surface currents and the scattered fields are expanded and solved up to the second order. The theoretical results are illustrated by calculating the bistatic and backscattering coefficients. It is shown that as the correlation length of the random roughness increases, the bistatic scattering pattern of the scattered fields show several beams associated with each Bragg diffraction direction of the periodic surface. When the correlation length becomes smaller, then the shape of the beams become broader. The results obtained using the EBC method is also compared with the results obtained using the Kirchhoff approximation. It is shown that the Kirchhoff approximation results show quite a good agreement with EBC method results for the VV and HH polarized backscattering coefficients for small angles of incidences. However, the Kirchhoff approximation does not give depolarized returns in the backscattering direction whereas the results obtained using the EBC method give significiant depolarized returns when the incident direction is not perpendicular to the row direction of the periodic surface.

We have also derived a general mixing formula for discrete scatterers immersed in a host medium. The inclusion particles are assumed to be ellipsoidal. The electric field inside the scatterers is determined by quasistatic analysis, assuming the diameter of the inclusion particles to be much smaller than the wavelength. The results are applicable to general multiphase mixtures, and the scattering ellipsoids of the different phases can have different sizes and arbitrary ellipticity distribution and axis orientation, i.e., the mixture may be isotropic or anisotropic. The resulting mixing formula is nonlinear and implicit for the effective complex dielectric constant, because the approach in calculating the internal field of scatterers is self-consistent. Still, the form is especially suitable for iterative solution. The formula contains a quantity called the apparent permittivity, and with different choices of this quantity, the result leads to the generalized Lorentz - Lorenz formula, the generalized Polder - van Santen formula, and the generalized coherent potential - quasicrystalline approximation formula. Finally, the results are applied to calculating the complex effective permittivity of snow and sea ice.

The study of the strong fluctuation theory for a bounded layer of random discrete scatterers are extended to include high-order co-polarized and cross-polarized second moments. The backscattering cross sections per unit area are calculated by including the mutual coherence of the fields due to the coincidental ray paths and that due to the opposite ray paths which are corresponding to the ladder and cross terms in the Feynman diagrammatic representation. It is proved that the contributions from ladder and cross terms for co-polarized backscattering cross sections are the same, while the contributions for the cross-polarized ones are of the same order. The bistatic scattering coefficients in the second-order approximation for both the ladder and cross terms are also obtained. The enhancement in the backscattering direction can be attributed to the contributions from the cross terms.

We have derived the dyadic Green's function for a two-layer anisotropic medium. The Born approximation is used to calculate the scattered fields. With a specified correlation function for the randomness of the dielectric constant, the backscattering cross sections are evaluated. The analytic expressions for backscattering coefficients are shown to include depolarization effects in the single-scattering approximation. It is also shown that the backscattering cross section (per unit area) of horizontal polarization can be greater than that of vertical polarization even in the case of half-space. The bistatic scattering coefficients are first calculated and then integrated over the upper hemisphere to be subtracted from unity, in order to obtain the emissivity. The principle of reciprocity is then invoked to calculate the brightness temperatures. It is shown that both the absorptive and randomly fluctuating properties of the anisotropic medium affect the behavior of the resulting brightness temperatures both in theory and in actual controlled field measurements. The active and passive results are favorably matched with the experimental data obtained from the first-year and the multiyear sea ice as well as from the corn stalks with detailed ground-truth information.

Electromagnetic wave propagation and scattering in an anisotropic random medium has been examined with Dyson equation for the mean field which is solved by bilocal and nonlinear approximations and with Bethe-Salpeter equation for the correlation of field was derived and solved by ladder approximation. The effective propagation constants are calculated for the four characteristic waves associated with the coherent vector fields propagating in an anisotropic random medium layer, which are the ordinary and extraordinary waves with upward and downward propagating vectors. The z-component of the effective propagation constant of the upward propagating wave is different from the negative of that of the downward propagating wave, not only for the extraordinary wave but also for the ordinary wave. This is due to the tilting of the optic axis which destroyes the azimuthal symmetry.

Since both snow and ice exhibit volume scattering effects, we model the snow-covered ice fields by a three-layer random medium model with an isotropic layer to simulate snow, an anisotropic layer to simulate ice, and the bottom one being ground or water. The snow and ice are characterized by different dielectric constants and correlation functions. The theoretical results are illustrated for thick first-year sea ice covered by dry snow at Point Barrow and for artificial thin first-year sea ice covered by wet snow at CRREL. The radar backscattering cross sections are seen to increase with snow cover for snow-covered sea ice, because snow gives more scattering than ice. The results are also used to interpret experimental data obtained from field measurements.

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